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APPLICATION OF A SHOCK-TURBULENT BOUNDARY LAYER INTERACTION THE--ETC(U)
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This paper describes the application of a non-asymptotic triple-deck theory of transonic shock-turbulent boundary layer interaction as a local modular element in the global calculation of supercritical airfoil flow fields.

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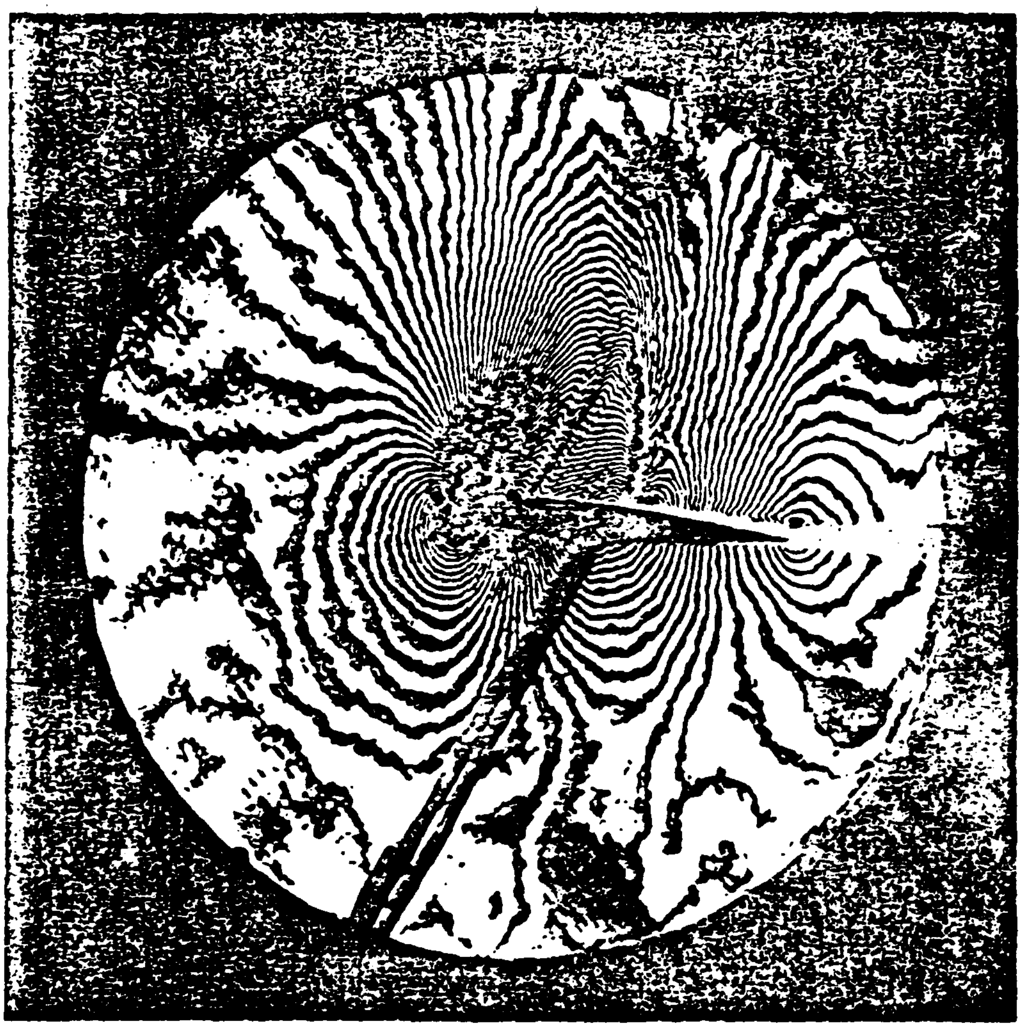
TRANSONIC PERSPECTIVE

A Critique of Transonic Flow Research



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APPLICATION OF A SHOCK-TURBULENT BOUNDARY LAYER INTERACTION THEORY IN TRANSONIC FLOW FIELD ANALYSIS

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APPLICATION OF A SHOCK-TURBULENT BOUNDARY
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FLOW FIELD ANALYSIS

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1. INTRODUCTION

Shock-boundary layer interaction can significantly influence not only the local transonic flow on missiles, wings and turbine blades but its influence can also extend downstream within the boundary layer and thereby alter the global aerodynamic properties of lift, drag and pitching moment. It is therefore important that shock-boundary layer interactions and their Reynolds and Mach number-scaling be properly modeled in engineering flow field prediction methods for supercritical aerodynamic bodies. This paper describes the application of a non-asymptotic triple deck theory of transonic shock-turbulent boundary layer interaction which provides such a tool for non-separating two-dimensional flows over a wide range of practical Reynolds numbers. Section 2 contains a brief description of the essential features of the theoretical model. Sections 3 and 4 then describe how the results of a comprehensive parametric study of this theory may be used to develop a generalized "viscous wedge" model of the local interaction which embodies proper scaling behavior as well as an approximate account of incipient separation that is in good agreement with experimental trends. In Section 5 we examine the application of this theory as an element in global viscous flow field analyses of supercritical airfoils. In such problems it will be shown that even in non-separating cases the changes across the interaction may significantly alter the subsequent turbulent boundary layer behavior for appreciable distances, especially when larger downstream adverse pressure gradients are present.

2. BRIEF OUTLINE OF THE LOCAL INTERACTION THEORY

Unlike significantly-separated flow where the disturbance flow pattern associated with a nearly-normal shock-boundary layer interaction is a very complicated one involving a bifurcated shock pattern[1], the unseparated case pertaining to turbulent boundary layers up to roughly $M_1 \approx 1.3$ has instead a much simpler type of interaction pattern which is more amenable to analytical treatment. With some judicious simplifications, it is possible to construct a fundamentally-based approximate theory of the problem in the latter case. Consider a known adiabatic boundary layer profile $M_0(y)$ subjected to small transonic disturbances due to an impinging weak and nearly normal shock. In the practical Reynolds number range of interest here ($10^5 \le Re_L \le 10^8$), it has been established[2-4] that the local interaction disturbance field in the neighborhood of the impinging shock organizes itself into three basic layered regions or "decks" (Fig. 1): 1) an outer region of potential inviscid flow above the boundary layer, which contains the incident shock and interactive wave systems; 2) an intermediate deck of frozen shear stress-rotational inviscid disturbance flow occupying the outer 90% or more of the incoming boundary layer thickness; 3) an inner shear disturbance sublayer adjacent to the wall which accounts for the interactive skin friction perturbations (and hence any possible incipient separation) plus most of the upstream influence of the interaction. The "forcing function" of the problem here is thus impressed by the outer deck upon the boundary layer; the middle deck couples this to the response of the inner deck but in so doing can itself modify the disturbance field to some extent, while the slow viscous flow in the thin inner deck reacts very strongly to the pressure gradient disturbances imposed by these overlying decks. In treating this interactive field we employ a non-asymptotic method that is an extension to turbulent flow of Lighthill's approach[6] because of its essential soundness and adaptability to practical engineering problems, similarity to related types of multiple-deck approaches that have proven highly successful in treating turbulent boundary layer response to strong adverse pressure gradients, and the large body of turbulent boundary layer interaction data plus recent numerical studies with the full Navier-Stokes equations which support the predicted results in a variety

of problems (see the survey in Ref. 5). Moreover, this approach provides at realistic Reynolds numbers a treatment of the inner deck pressure gradient terms plus the middle deck $\partial p/\partial y$ and streamline divergence effects, along with simplifying approximations that render the resulting theory tractable from an engineering standpoint.

A very detailed description of the above-mentioned non-asymptotic triple deck analysis can be found in Refs. 5 and 7 and hence will not be given here. The resulting predictions, such as typically illustrated in Fig. 2, describe all the essential global features of the mixed transonic character of the non-separating normal shock-turbulent boundary layer interaction problem including the interactive pressure distribution and upstream influence, displacement thickness and local shape factor, and interactive skin friction up to incipient separation. This interaction theory employs for the incoming turbulent boundary layer velocity profile a very general Composite Law of the Wall-Law of the Wake profile model due to Walz[8], which is characterized by three parameters (M_1, boundary layer thickness Reynolds number and the incoming shape factor). The influence of both shock obliquity[9] and wall curvature[10] have also been examined in detail and incorporated into the theory. Very extensive parametric studies and detailed comparisons with experiment have shown that it gives a very good account of all the important engineering features of the interaction over a wide range of Mach and Reynolds number conditions. Moreover, the important but heretofore-ignored influence of incoming boundary layer shape factor H_{1_i} (and hence the upstream pressure gradient history) has been determined[5,7].

3. A GENERALIZED VISCOUS-RAMP MODEL OF THE INTERACTION

In certain engineering applications to global flow field analysis computer programs for wings or turbine blades, it has proved expedient to model the interaction as a simple local inviscid δ^* - "bump" or "ramp." A serious deficiency of this approach is that it does not account for the dependence of the bump shape and size on Reynolds number, shock strength and boundary layer shape factor, while the additional interaction effects on the downstream boundary layer (such as C_f reduction) are ignored altogether. With the aforementioned parametric study results in hand, however, the present theory provides a much improved "viscous ramp" representation of the interaction (see Fig. 3A) whose key physical features have the correct dependence on M_1, $Re_{\delta*}$ and H_{1_i}.

Results for these viscous wedge properties taken from Ref. 11 are presented in Figs. 3B-3E, where the upstream and downstream influence distances, the slope and overall height of the δ^* - bump are plotted along with the downstream C_f/C_{f_0} values that may be needed along with δ^* to re-initialize a subsequent turbulent boundary layer calculation downstream. We note in general that the overall scale of the interaction (which can be a sensitive effect in both steady and unsteady applications where such viscous wedge models are employed) does not scale according to the undisturbed boundary layer thickness even in the non-separating case. It is further noted that the viscous wedge slopes are in rough agreement with the maximum attached shock deflection value observed empirically[12], although here of course there is a dependence on Re_δ and H_{1_i} as well as Mach number. Finally, in all of these curves we see a significant dependence on the incoming boundary layer shape factor that would appear to be an important consideration in practical applications.

Closed-form analytical fits to the various curves of Fig. 3 have been developed[11] which provide a very rapid yet complete modeling of the local interaction effects for incorporation as a local module in global inviscid-boundary layer analysis or design programs for supercritical airfoils.

4. INCIPIENT SEPARATION

The present theory, although it breaks down at separation, does yield a useful indication of incipient separation where $C_{f_{min}} \to 0$, owing to the particular attention paid to the treatment of the local interactive skin friction behavior[5]. Since this indication is of great practical interest, a parametric study of incipient separation conditions inherent in the present theory was carried out; the results for a normal shock on a flat surface are presented in Fig. 4A where the shock Mach number above which incipient separation occurs is plotted as a function of the Reynolds number with the shape factor as a parameter; also shown in the Figure is the approximate experimental boundary determined by a careful examination[11] of a large number of transonic interaction tests, besides Nussdorfer's[13] $M \sim 1.30$ criterion for turbulent flow. It is seen that the theoretical prediction of a gradual increase in the incipient separation Mach number value with Reynolds number is in agreement with the trend of the data; moreover, the theoretical prediction of only a small influence of shape factor on the incipient separation conditions is also borne out by the lack of any consistent H-effect for the same Re discernible in the data (Squire has observed a similar insensitivity to H_{i_f} in purely supersonic flow interactions[14]). The absolute values of the incipient separation Mach number predicted by the present interaction theory are seen to be consistently slightly lower than the average experimental value; this is attributable to the combined effects of the linearized inner deck theory (which over-predicts the pressure gradient effect on C_f) and the assumption of a normal shock when in fact most of the experiments likely entail some shock obliquity (which also delays separation to somewhat higher shock-strengths). It is interesting to note that Nussdorfer's[13] original incipient separation criterion, based as it was on a very limited base, does roughly go through the average of the data although it does not account for the proper Reynolds number effect.

Fig. 4B shows the influence of wall curvature; it is seen to have only a small effect in delaying incipient separation to a slightly higher shock strength for a given Re_L and H_i, this being of the same order as the experimental data band.

5. APPLICATION TO GLOBAL FLOW FIELD ANALYSIS

5.1 Downstream Effects from a Shock-Boundary Layer Interaction

In addition to the increased displacement thickness, the foregoing discussion shows that the skin friction level following the interaction is significantly reduced; combined with the attendant sensitivity to the profile shape, this suggests that the subsequent downstream boundary layer development may retain a memory of the interaction effects for a considerable distance (over and above a simple thickening), particularly as regards possible incipient separation in any adverse pressure gradients downstream. As indicated in Fig. 5 this downstream "interaction after-effect" in the boundary layer influences the sensitive trailing edge region and thus may be important in the design and analysis of rear-loaded airfoils, especially at higher lift coefficients with increasingly-aft shock locations; it likewise may be important on three dimensional wing configurations where the shock interaction zones are well aft.

The aforementioned after-effect question was therefore subjected to detailed study using the two-layer turbulent boundary layer program of Moses[15] as a model of the downstream viscous flow; the program is coupled to the present interaction theory by initializing it with the post-interactive flow properties so as to account fully (both C_f and δ^*), partially (δ^* only) or not at all for the changes across the interaction. Calculations were then made of the subsequent downstream turbulent boundary layer behavior (H, C_f, θ^*, δ^*) in various constant post-shock adverse pressure gradients typical of airfoils for different assumed local interactive shock strengths and positions or Reynolds numbers. The results serve as a paradigm of the downstream sensitivity question in real flows.

A variety of cases were studied[16], typical results of which are presented in

Fig. 6 where we show the predicted behavior of the boundary layer shape factor and skin friction in three increasingly-strong adverse pressure gradients downstream of an interaction occurring at a typically rearward position; the consequences of fully, partially or negligently-treating the boundary layer changes across the interaction are indicated. Generally, it is seen that the downstream behavior of the boundary layer is indeed sensitive to detailed modeling of the interactive effects and that this sensitivity increases with the strength of the downstream adverse pressure gradient. The adverse pressure gradient magnifies the subsequent influence of the skin friction (as well as the δ^*-rise) across the interaction so that downstream separation tends to occur earlier than would be predicted by either neglecting or treating only the δ^* effect of the upstream interaction. As shown in Fig. 7, these predictions are supported by a comparison with boundary layer measurements downstream of a non-separating shock interaction zone on a supercritical airfoil; both the skin friction and shape factor data are poorly predicted when the interaction is neglected but are reasonably well predicted when the complete interaction effects are taken into account.

Examination of many such results leads to the further conclusion that such interactive after-effects extend at least 20-30% chord distances downstream on a typical airfoil or wing and increase (as expected) with either larger shock strength or decreasing Reynolds number. If the trailing edge region lies within this range of the shock, it is thus seen that a simple thickening effect alone is not sufficient to account for the interaction and may result in an inaccurate prediction of the rearward boundary layer shape factor, skin friction and incipient separation properties including their scaling. This is of practical importance for two major reasons: 1) in regions of sustained adverse pressure gradient that often follow the short-scale interaction zone, the shape of the velocity profile and streamwise shear stress distribution (as well as thickness) are of considerable importance to the aerodynamic design of an airfoil or wing; 2) the altered boundary layer properties (especially possible incipient separation) near the trailing edge and into the wake can further exert a powerful effect on the overall aerodynamics via their influence of the Kutta condition[17] and on possible buffet onset.

5.2 Supercritical Wing Section Flow Fields

Nandanan et al[12] have carried out an even more detailed study of interactions on actual supercritical airfoils including experimental comparisons. They developed a global computational method for transonic airfoil flow analysis which incorporates the present analytical solution for near-normal shock-boundary layer interaction into a state-of-the-art viscous-inviscid computation code. Theoretical results obtained with this method were compared to representative data from boundary layer and surface pressure measurements on three transonic airfoils in the DFVLR-AVA (Göttingen) Transonic Wind Tunnel; some examples of these comparisons are shown in Figs. 8A and 8B. The agreement between theory and experiment in both the boundary layer displacement thickness and the surface pressure distributions was, for all test cases considered, quite good. The associated predictions of the local skin friction variation through the interaction zone also agree reasonably well with the values inferred from the experimental boundary layer profiles via the Ludwig-Tillman relation (see, e.g., Fig. 9).

The results of this investigation indicated that treating the shock-boundary layer interaction by conventional boundary layer theory generally leads to a slight underprediction of the displacement thickness immediately downstream of the shock and, due to the amplifying effect of the sustained rear adverse pressure gradients, to an appreciable underestimation of the displacement thickness at the trailing edge (see Fig. 10). The latter is also clearly reflected in the pressure distributions and aerodynamic coefficients compared. Considering these results, one may conclude that it is generally necessary to include a physically correct treatment of shock wave-boundary layer interaction in the analysis of transonic airfoil flow.

6. CONCLUDING REMARKS

The results of this study have shown that it is now possible to incorporate as an interactive module within a global flow field analysis the correctly-modeled (and scaled) local shock-boundary layer interaction effects for the non-separating case. The non-asymptotic triple deck interaction theory involved covers a wide range of practical Reynolds numbers and turbulent boundary layer profile shape factors including the effect of wall curvature; moreover, it gives an approximate indication of when incipient separation occurs. It was further shown that such theory is generally desirable when accurate predictions are desired in the important trailing edge region of rear-loaded supercritical airfoils because the detailed changes across an upstream interaction can significantly alter the subsequent turbulent boundary layer behavior for appreciable distances downstream.

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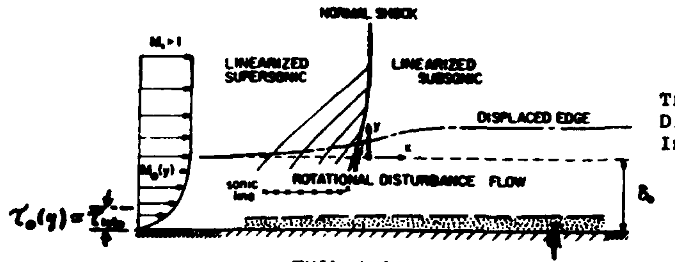


Fig. 1

Triple-Deck Structure of the Local Disturbance Field in a Transonic Interaction.

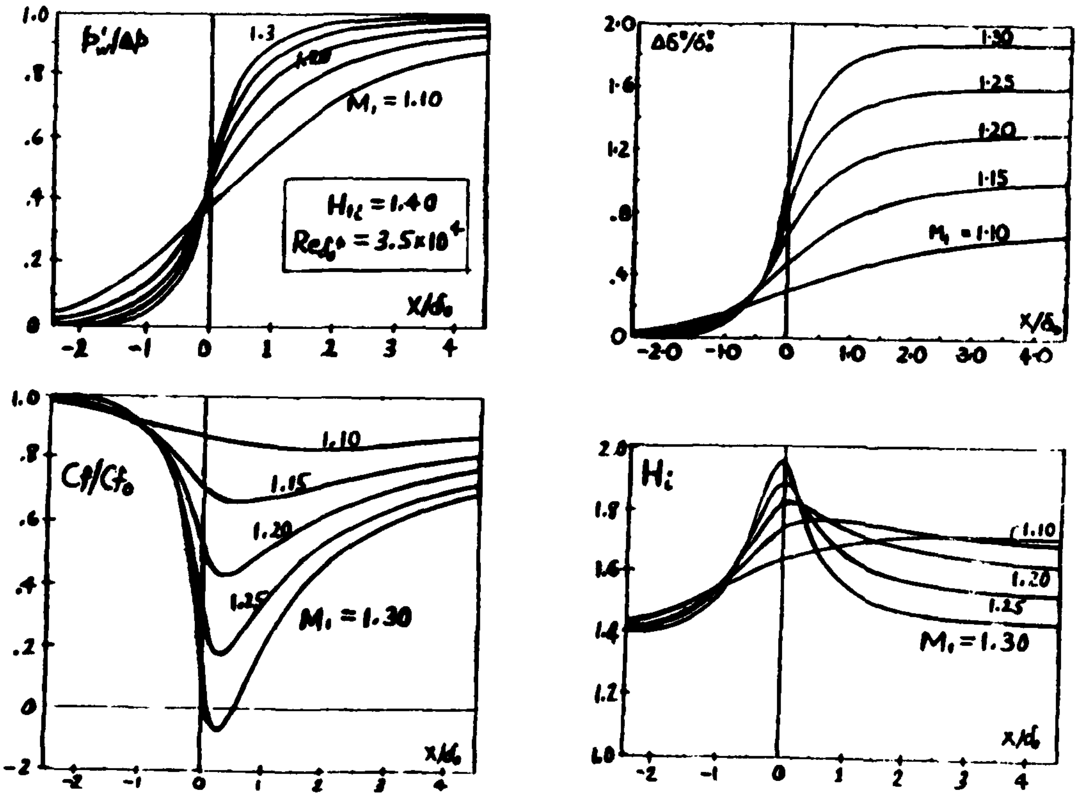


Fig. 2 Typical Features of Normal Shock-Turbulent Boundary Layer Interactions Without Separation

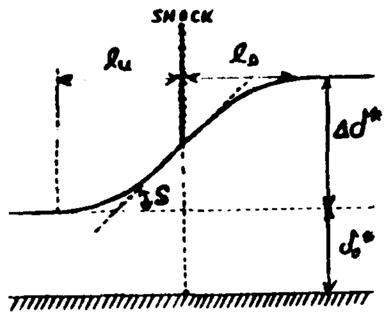
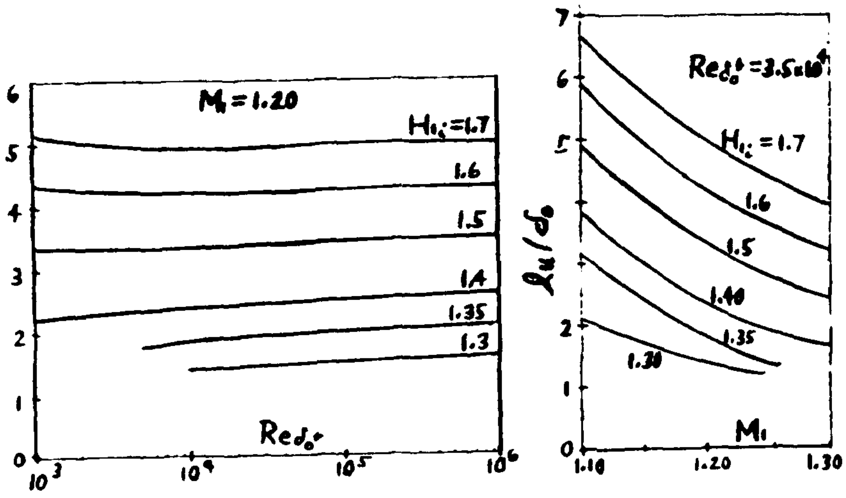


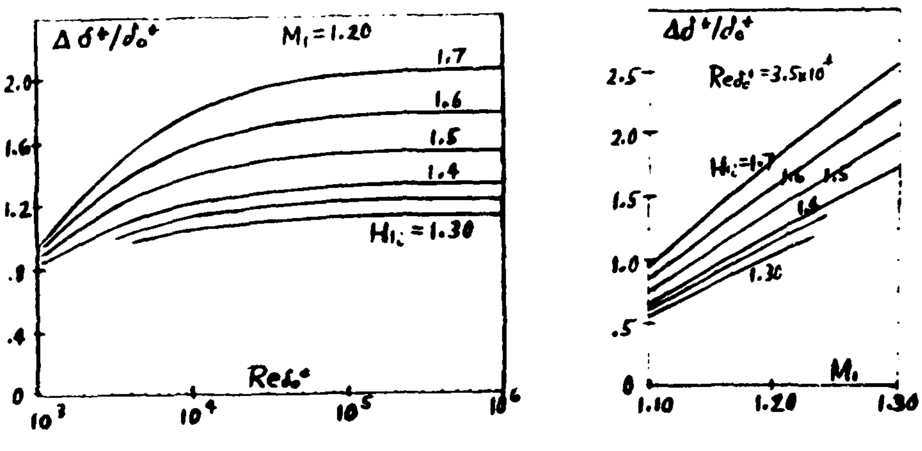
Fig. 3A

Parametric Study of Viscous Wedge Interaction Model



3B

Upstream Influence Distance



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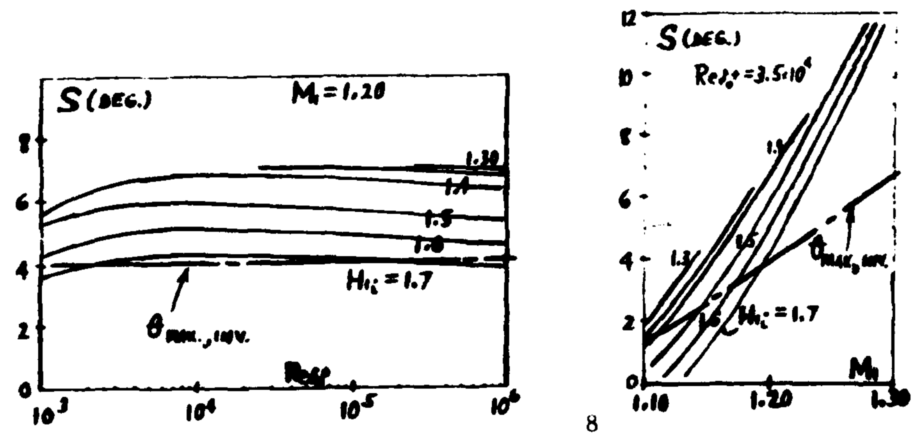
Overall Displacement Thickening



3D

Viscous Wedge Slope

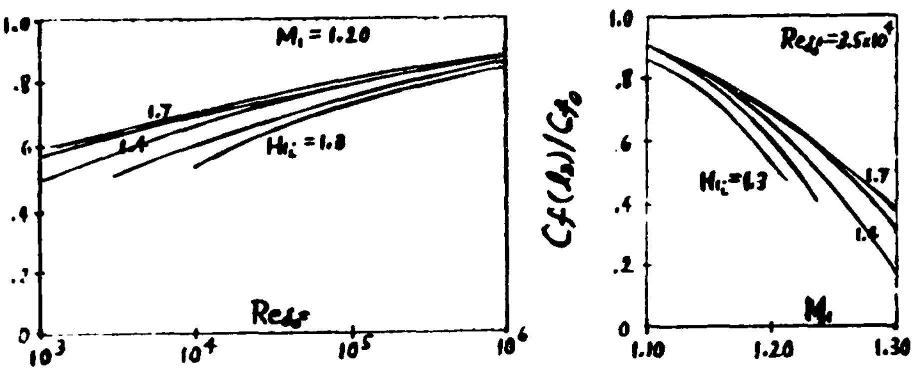
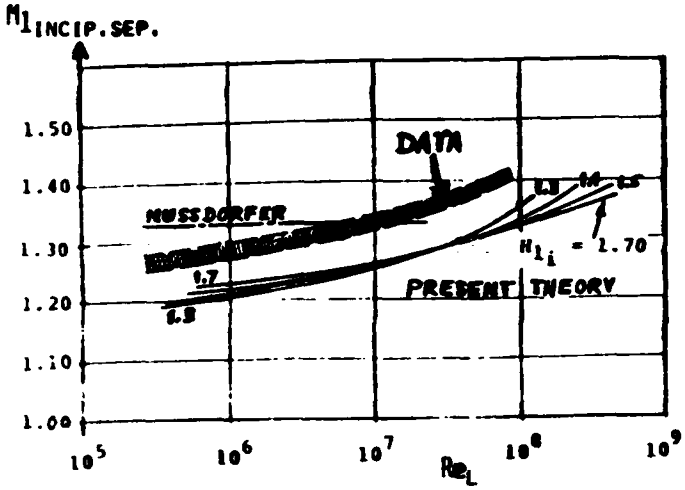


Fig. 3E

Post-Interactive

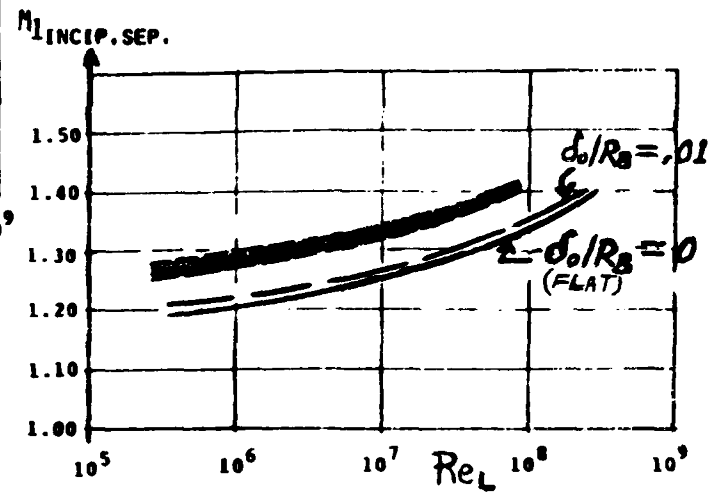
Skin Friction Level



a. Flat Surfaces

Fig. 4

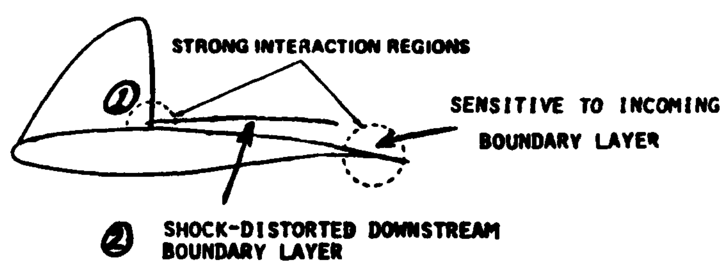
Incipient Separation Conditions



b. Curved-Wall Effect
($H_{1_i} = 1.40$)

Fig. 5

The Global Viscous-Inviscid Interaction Problem for Supercritical Airfoils (Schematic)



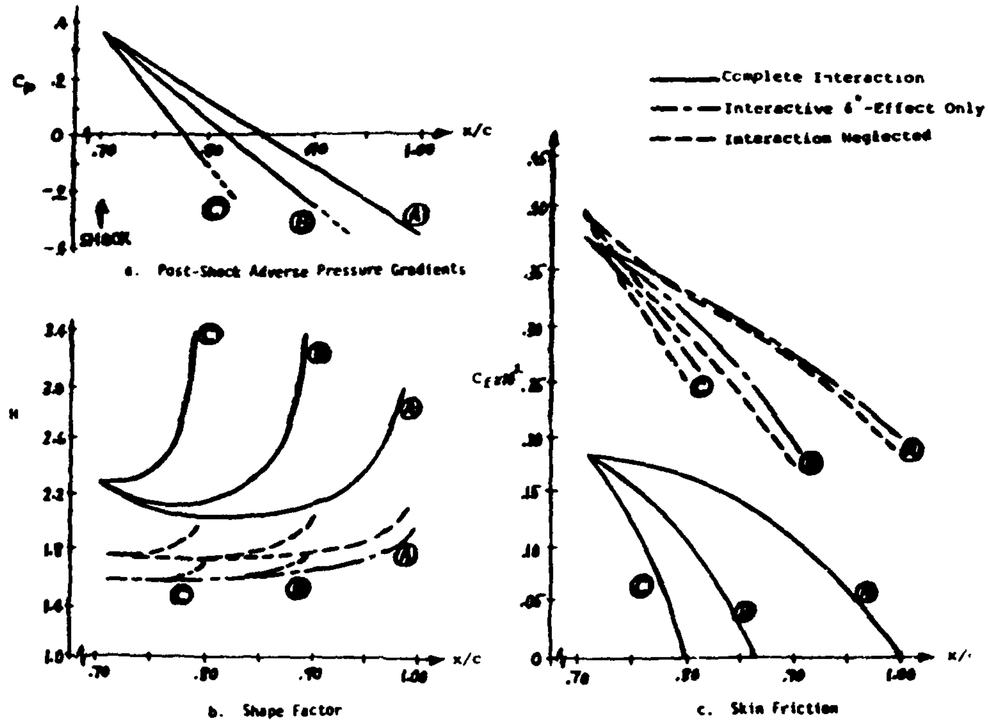


Fig. 6
Sensitivity Study of Interaction Effects on Downstream Turbulent Boundary Layer Behavior

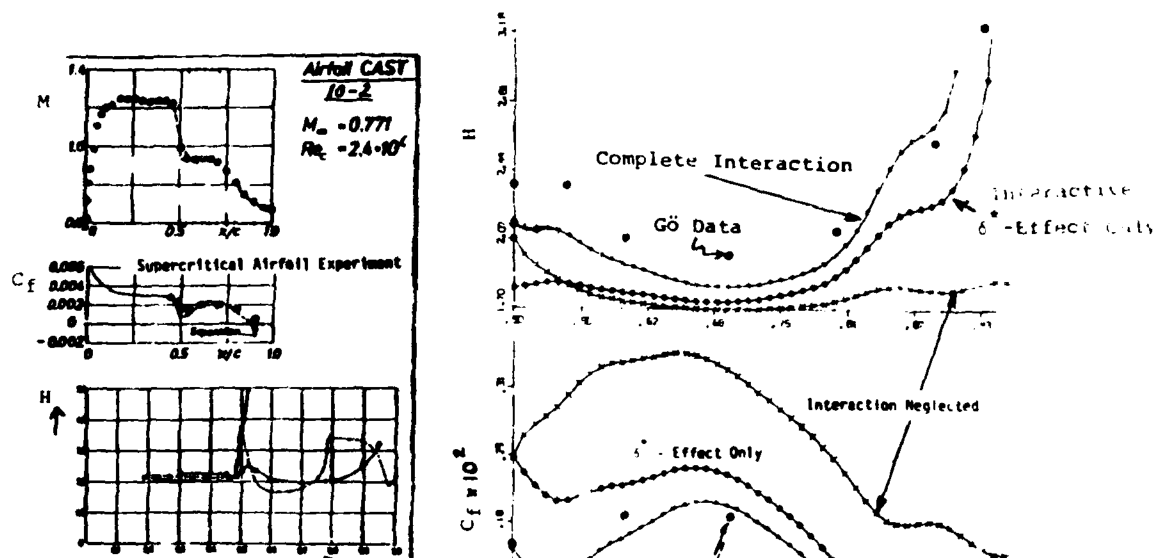
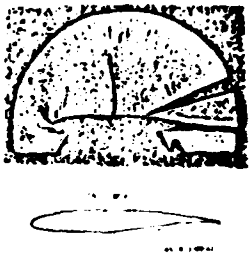
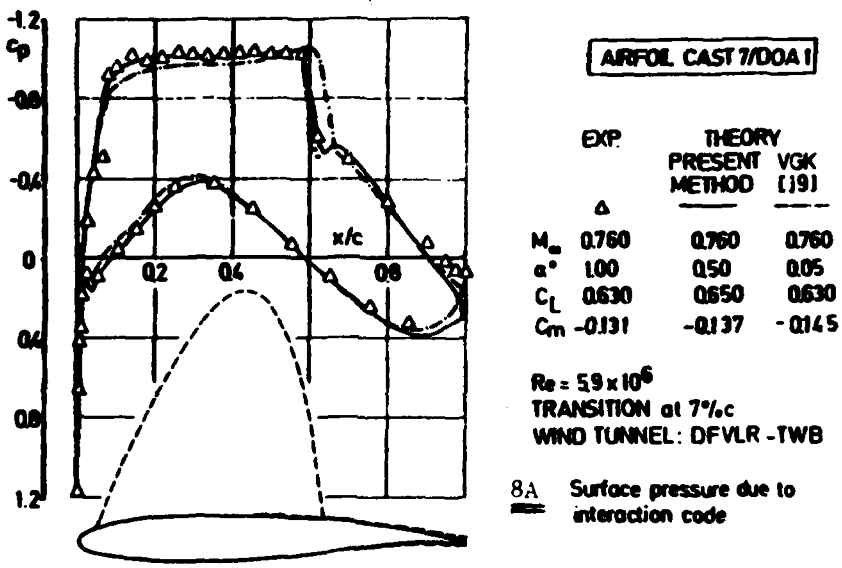
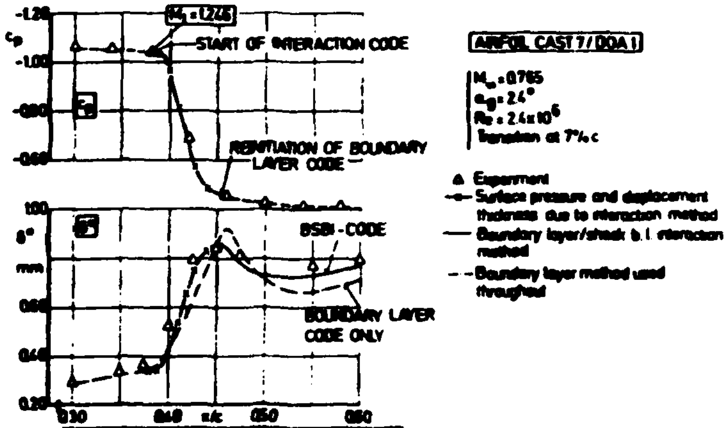


Fig. 7
Comparison of Post-Interaction Turbulent Boundary Layer Predictions with Experiment on a Supercritical Airfoil





8A Surface pressure due to interaction code



8B Details in the Interaction Region

Fig. 8

Comparison of Present Method with Experiment and VGK-method. Airfoil CAST 7/DOA1

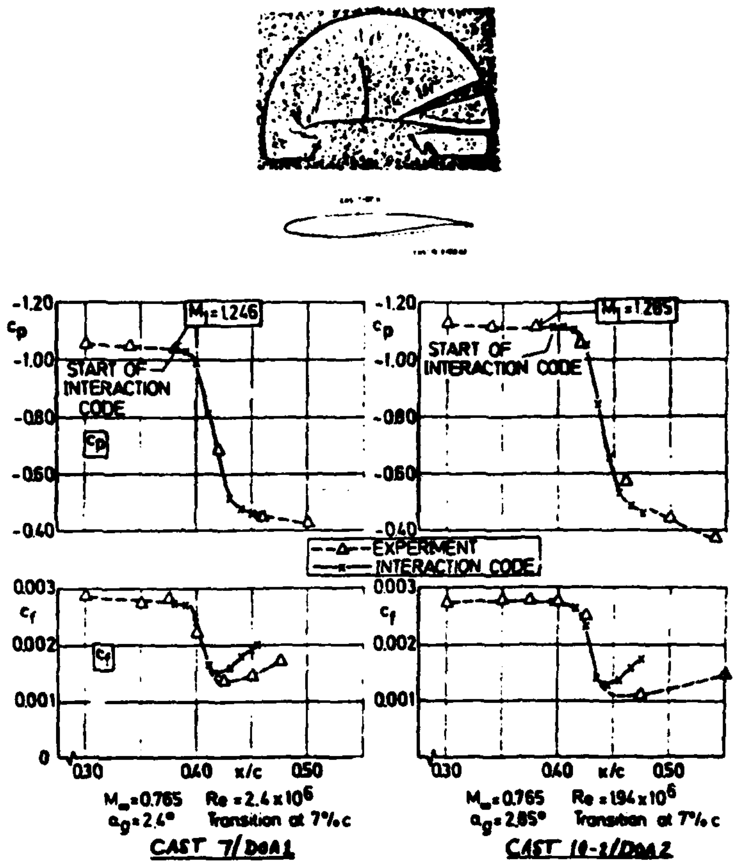


Fig. 9 Comparison of Present Interaction Theory with Experimental Data of Stanewsky (DFVLR-Gö)

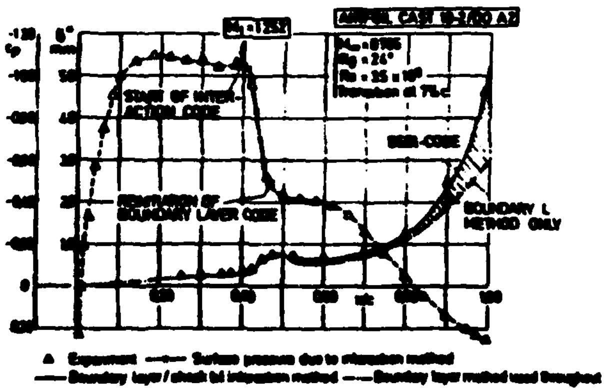


Fig. 10 Comparison of δ^*-distributions Obtained by Boundary Layer Code, BSBI-code and Experiment. Airfoil CAST 10-2/DOA2

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